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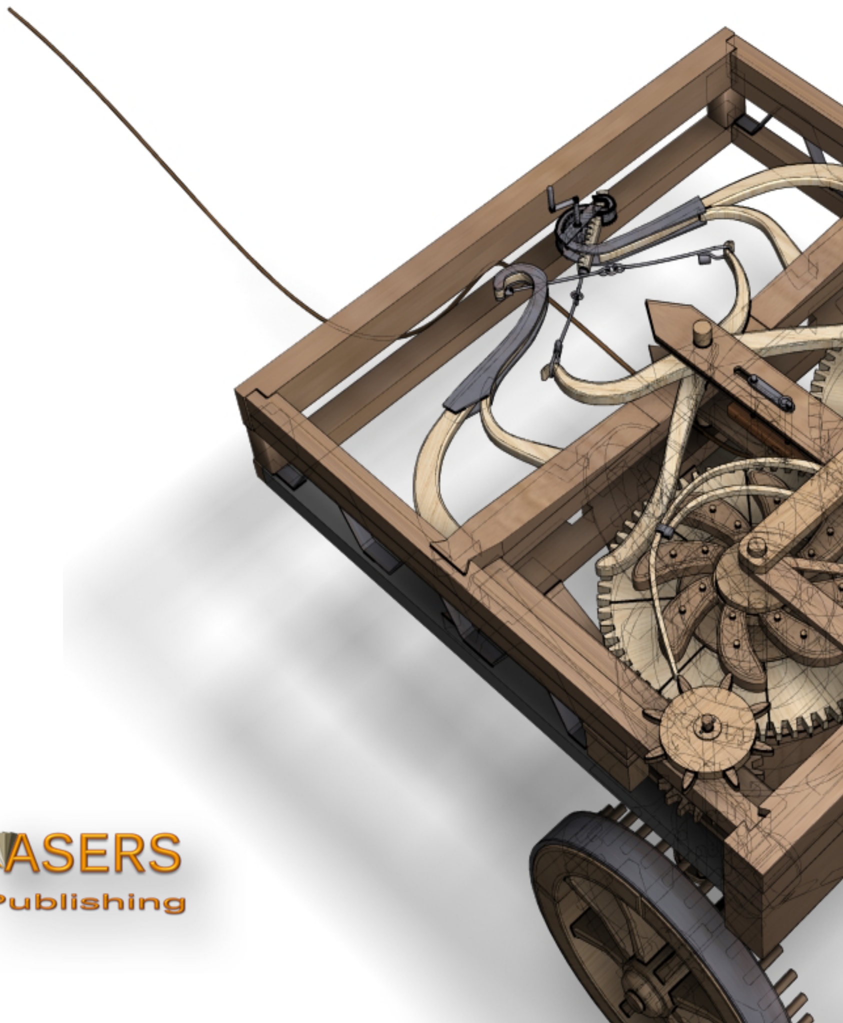

Quarterly
Volume XV
Issue 1(73)
Spring 2024
ISSN 2068 – 7729
Journal DOI
https://doi.org/10.14505/jemt

ASERS Publishing

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Table of Contents

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Volume XV, Issue 2(74)
Journal of Environmental Management and Tourism

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Deadline for submission:	15st April 2024
Expected publication date:	1 June 2024
Website:	https://journals.aserspublishing.eu/jemt
E-mail:	jemt@aserspublishing.eu

DOI: https://doi.org/10.14505/jemt.v15.1(73).04

Rapid Bathymetry Mapping Based on Shallow Water Cloud Computing in Small Bay Waters: Pilot Project in Pacitan-Indonesia

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Article's Info: Received 05 December 2023; Received in revised form 23 December 2023; Accepted 19 January 2024; Published 29 February 2024.

Abstract: Mapping coastal areas generally requires large data constellations in time series and requires analysis using complex mathematical and modeling approaches. In shallow-water bathymetric mapping, remote sensing plays an important role in supporting conventional bathymetric mapping, especially in areas that are difficult to access. This method called Satellite Derived Bathymetry (SDB). The cloud computing approach is a solution for mapping shallow water bathymetry rapid and effectively. This study using Google Earth Engine (GEE) to compute remote sensing data for produce near-shore bathymetry. The method of Li *et al.* (2021) performs bathymetric extraction without using depth samples but uses chlorophyll-A as input for depth extraction parameter calculations. This study examines a small bay in the waters of Pacitan, Anakan Bay, and the waters of Kemujan Island in the Karimunjawa Islands. Within this study area, significant differences in resulting depth are very limited, ranging from 0 to -17.8. The developed model, based on the algorithm proposed by Li *et al.* (2021), is estimated to be able to provide accurate predictions of up to around 90% in the waters studied, with a root mean error rate (RMSE) of 1.1 meters.

Keywords: SDB; cloud computing; GEE; bathymetry.

JEL Classification: Q57; Q25; R11.

1. Research Background

Monitoring environmental issues, especially in the coastal areas will require access to large volumes of geospatial data and time series (Rumson, Hallett, and Brewer 2017; Bousquin 2021; Ghosh and Mistri 2022; Putman *et al.* 2023), in addition, using raster geospatial data makes it possible to carry out complex mathematical modeling operations with the support of Geographic Information Systems (Zhang *et al.* 2021) The natural and non-natural phenomena on the coast have become very dynamic (Bhargava, Sarkar and Friess 2020), in the other side can be mapped rapid and efficiently using the cloud computing approach (Goldberg, *et al.* 2014; Xu *et al.* 2022). Cloud computing can play a significant role in the process of accelerating coastal area mapping, especially shallow water bathymetry mapping, which has the benefit of supporting navigation safety in coastal areas. The bathymetry which is able to describe the depth of waters is the key to making in-depth observations in the marine environment. On the other hand, information regarding shallow water bathymetry is crucial when faced with the need for management and monitoring of coral reefs and ecosystem protection (Zhang, Ma, and Zhang 2020). Conventionally, bathymetric mapping using single or multibeam instrument requires complex equipment, limited area coverage, high operational costs and relatively long processing time, so it is less effective when used to map shallow waters which are usually close to coastal areas (Arief *et al.* 2013; Kurniawan, *et al.* 2021; Salameh *et al.* 2019). The use of bathymetry obtained through multispectral imagery taken by satellites has become a major focus in research over the last few decades because it is an efficient tool for evaluating the depth of waters, especially shallow waters (Lyzenga 1985; Philpot 1989; Bierwirth, Lee, and Burne 1993; Stumpf, Holderied, and Sinclair 2003; Lyzenga, Malinas, and Tanis 2006; Pe'eri, *et al.* 2014).

The remote sensing approach is the key to carrying out bathymetric mapping in shallow waters quickly and efficiently (Knudby, Ahmad, and Ilori 2016; Casal *et al.* 2020; Hodúl *et al.* 2020; Susa 2022), but in its implementation, shallow water bathymetric mapping based on remote sensing satellite data is a process with high complexity and challenges (Chen, Ma, and Zhang 2021; Alevizos, Le Bas, and Alexakis 2022; Wang *et al.* 2023) because generally there are atmospheric distortions in the optical band in the process of penetration into the bottom of the waters (short waves are generally better at penetrating waters), so that one satellite image system and another can produce different results (Marcello, Eugenio, Martín, and Marqués 2018). Bathymetric mapping of shallow waters using a remote sensing approach is known as "Satellite Derived Bathymetry (SDB)". Today's SDB can be used to map depth in shallow waters as far as the ability of solar radiation to penetrate the bottom of the water (Jégat, *et al.* 2016), with various algorithms that have been developed, including by (Lyzenga 1978; Van Hengel and Spltzer 1991; Bierwirth, Lee, and Burne 1993; Stumpf, Holderied, and Sinclair 2003; Li *et al.* 2021; Vinayaraj, Raghavan, and Masumoto 2016). SDB is technically capable of providing much more significant data processing speed compared to conventional surveys, however, with the development of cloud-based computing technology, the SDB process can be carried out more efficiently and optimally. Nowadays remote sensing images are increasingly varied (Landsat 9, SPOT 7, IKONOS, WorldView, Sentinel, PlanetScope, Rapid eye, etc.) making SDB data input increasingly diverse with accuracy at each level of spatial and temporal resolution of the image.

In the last decade, a variety of research and shallow water mapping projects based on remote sensing imagery have been developed. Vinayaraj, Raghavan, and Masumoto (2016) developed an SDB algorithm that determines regression coefficients by taking into account local factors in the Adaptive-Geographically Weighted Regression (A-GWR) framework. Then Chybicki (2018) utilized the 3-dimensional geographical weighted regression (3GWR) technique which combines the geographical weighted regression (GWR) model, with inverse optimization which considers depth. Lumban-Gaol, Ohori, and Peters (2022) using Convolutional Neural Networks (CNN) in machine learning approach. Generally, the implementation of SDB utilizes software based on remote sensing and GIS, but recently a more efficient approach using cloud computing has begun to be developed, namely by applying cloud computing on Google Earth Engine with a combination of Sentinel-2 data using the Lyzenga algorithm (1985) and Stumpf (2003) (Traganos *et al.* 2018). Furthermore Li *et al.* (2021) uses clean water Mosaic with minimal water column attenuation, thereby enabling automatic bathymetry estimation algorithms to reduce uncertainties caused by water column attenuation. Mudiyanselage *et al.* (2022) also utilizes machine learning algorithms through a cloud-based random forest approach to extract shallow water bathymetry information.

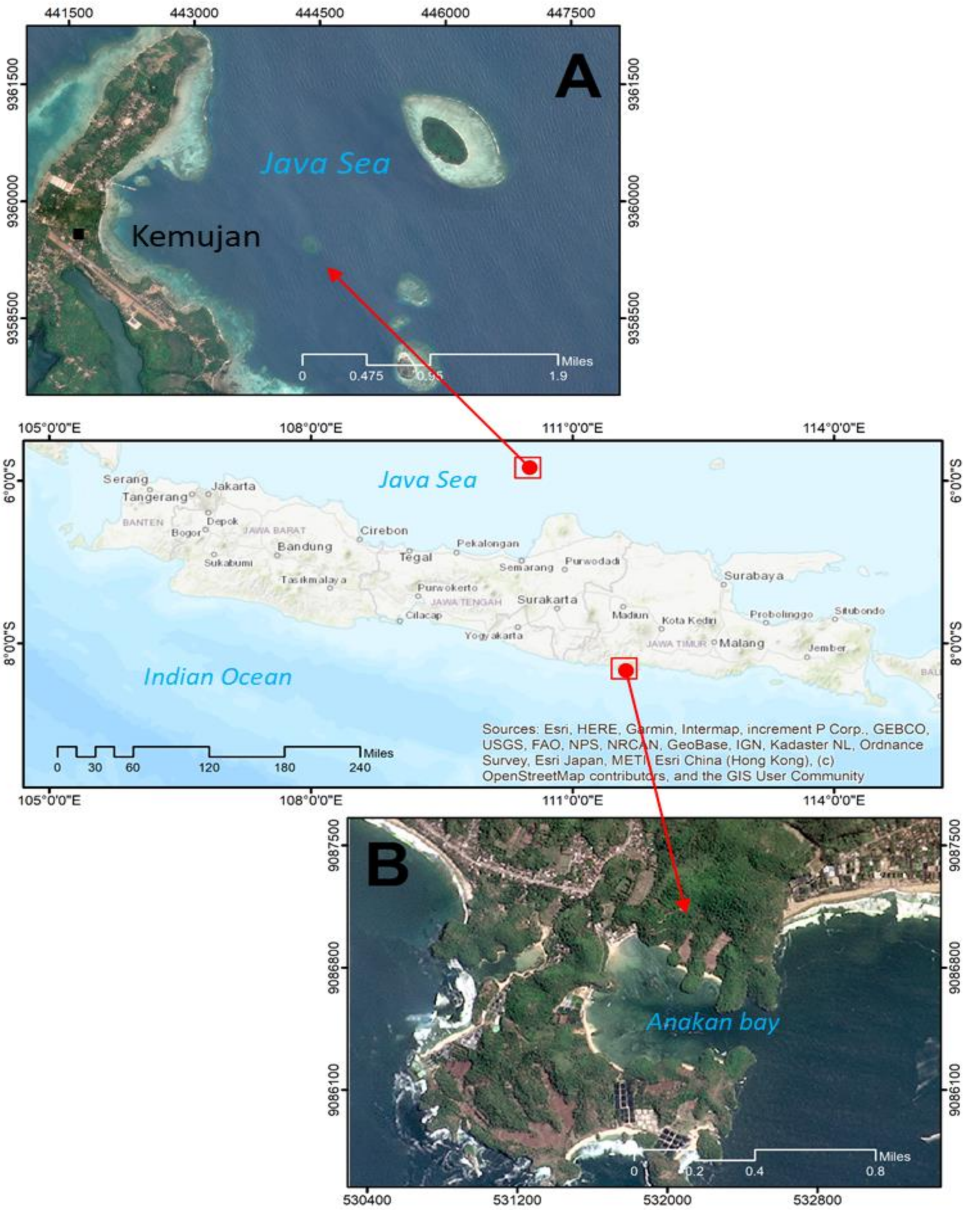
Based on this background, as a relatively new technology in geospatial data processing, cloud computing, which is generally used to carry out massive big data analysis, can also be used to obtain shallow water bathymetry information more effectively and optimally in terms of processing time. However, evaluation is still needed to monitor and control the quality of the data produced. In line with this statement, this research aims to applying Li *et al.* (2021) algorithm processing framework from upstream to downstream in one process frame on the cloud.

2. Site Study

This study was conducted in two optically shallow water areas that are geographically separated by the island of Java. The shallow water location used as a pilot project in this research is Small bay – Anakan Bay in Pacitan, then to be able to run the model that has been created it will also be tried for other areas including the Kemujan island which part of Karimun Jawa archipelago (Central Java Province) (see figure 1). The constellation of two research areas was chosen by considering the availability of datasets with clear water conditions around the bay.

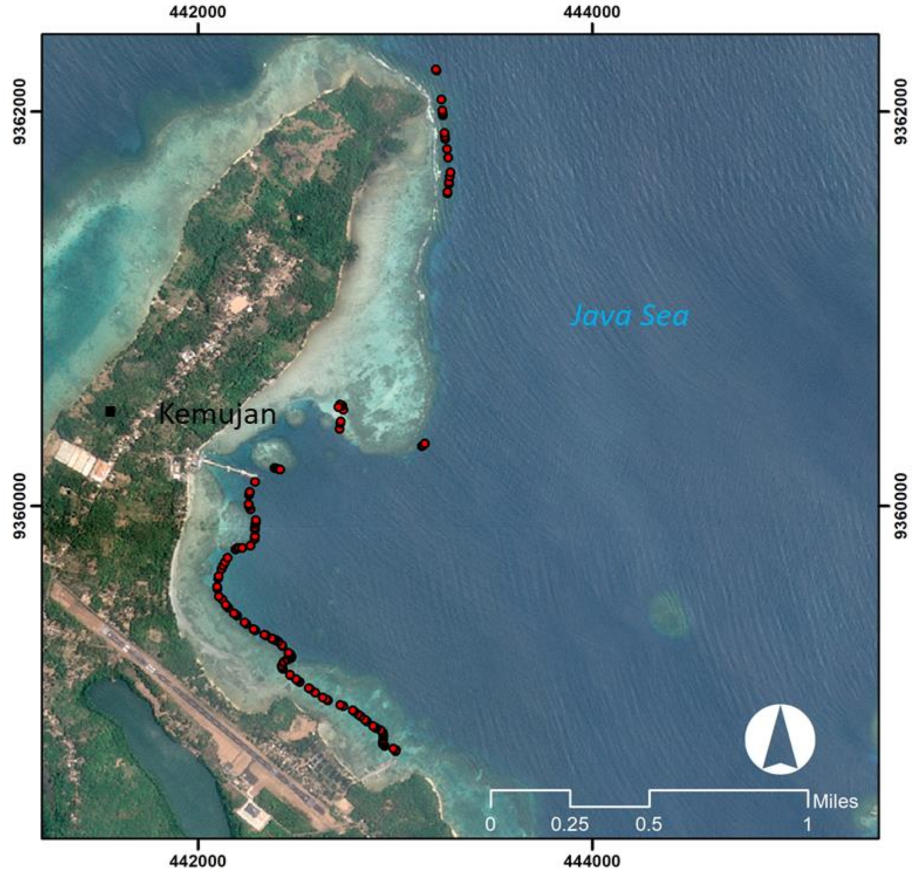
Water conditions are measured visually by separating shallow and deep water optically based on passive system remote sensing images. Geographically, the island of Java separates these two areas, but astronomically both are still included in the Southern Hemisphere and are included in the UTM Zone 49 M grid system. The astronomical position of Anakan Bay - Pacitan Regency is 08°15'48.26" LS, 111°17'20.43" E, while the Kemujan Island astronomically located at 5°47'8.98" N, and 110°28'46.21" E. In general, based on data that has been carried out by previous research by the constellation of two research areas was chosen by considering the availability of datasets with clear water conditions around the bay. Water conditions are measured visually by separating shallow sea and deep sea optically based on passive system remote sensing images. Geographically, the island of Java separates these two areas, but astronomically both are still included in the Southern Hemisphere and are included in the UTM Zone 49 M grid system. The astronomical position of Anakan Bay - Pacitan Regency is 08°15'48.26" LS, 111°17'20.43" E, while the research location on Kemujan Island – Karimunjawa Islands is astronomically located at 5°47'8.98" N, and 110°28'46.21" E. In general, based on data that has been carried out by previous research by Wicaksono (2015) on Kemujan Island, the dominant benthic habitats seen are macro algae, coral reef, seagrass and bare substratum.

Figure 1. The study location, where (A) is the location of Kemujan Island in the Karimunjawa Islands, and (B) Anakan Bay in Pacitan Regency.



The validation data used in this research comes from direct measurements in the field (in-situ). Due to limited data, validation was carried out in around Kemujan Island waters. Figure 2 provides an illustration of the location for in-situ data collection in 2016.

Figure 2. Depth sample points obtained through in-situ measurements in 2016 were used as validation reference data.



3. Solar Radiation Infiltration Process and Li *et al.* (2021) SDB Method

Shallow water is optically a unique area because sunlight can still penetrate to the bottom of the water. In practice, shallow waters only with clear water and not covered by organisms or other solid loads can be processed to SDB. Sunlight that penetrates the water surface is scattered and absorbed by water molecules and components, then the sensor will receive energy through reflected radiation from the shallow seabed layers. Furthermore, light entering the water layer is also absorbed and re-scattered by the water body and its substrate (see figure 3) (Lyzenga 1985). The physical aspect underlying the water depth prediction model from multispectral images is the attenuation of light in the water column. This is related to wavelength, where shorter wavelengths in the electromagnetic spectrum will dampen more minimally compared to longer wavelengths (Vinayaraj, Raghavan, and Masumoto 2016).

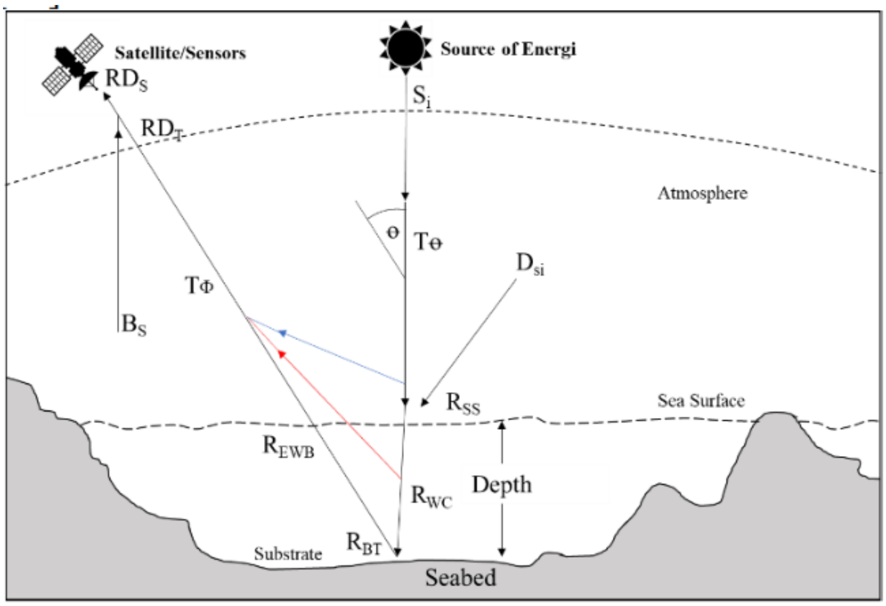
The method for automatically obtaining shallow water bathymetry was developed by Li *et al.* (2021) which specifically uses cloud-based computing via Google Earth Engine (GEE). The PlanetScope satellite image used is an image with minimum cloud cover, sunglint and turbidity in a certain period. Non-aquatic and aquatic objects in this study are separated with the help of NDWI (Normalized difference water index). The NDWI formulation is as follows:

$$NDWI = \frac{\rho(Green) - \rho(NIR)}{\rho(Green) + \rho(NIR)}$$

Li *et al.* (2021) developed an automatic bathymetric mapping method using cloud computing platform – google earth engine. Remote sensing reflectance (Rrs) is calculated from the mosaic surface reflectance ρ(λ) based on the equation constructed from as:

$$R_{rs}(\lambda) = \rho_m(\lambda)/\pi$$

Figure 3. Solar radiation enters the water column through various charges and water molecules before reaching the bottom of the water. The molecules and solid charge will influence the values reflected to the sensor, and become the basis for depth model predictions in the SDB (by Kurniawan *et al.* 2021 modified from Bierwirth, Lee, and Burne 1993)



Furthermore, the value of the calculation results of R_{rs} then used as a basis for carrying out r_{rs} as follows:

$$r_{rs}(\lambda) = \frac{R_{rs}(\lambda)}{0.52 + 1.7\, R_{rs}(\lambda)}$$

Li *et al.* (2021) estimating shallow water bathymetry by calculating different levels of attenuation from the blue and green bands. The basic difference used is that the parameters m_0 and m_1 are calculated using Chlorophyll-a (Chl-a) concentrations as a representation of clean offshore waters. Chlorophyll-a (Chl-a) concentration based on observations via marine copernicus (see: *https://marine.copernicus.eu/access-data/myocean-viewer*)

$$Depth = m_0 \frac{ln(1000 * r_{rs}blue)}{ln(1000 * r_{rs}green)} - m_1$$

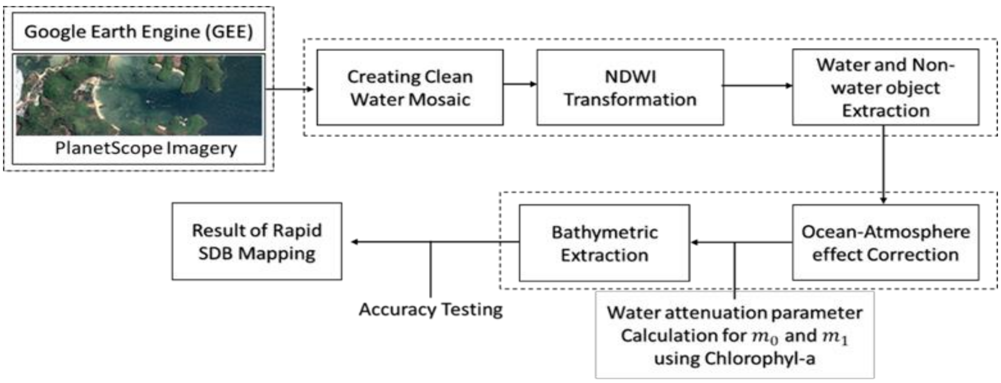
$$m_0 = 52.073 * e^{(0.957 * Chl_a)}$$

$$m_1 = 50.156 * e^{(0.957 * Chl_a)}$$

4. Research Methodology

Google Earth Engine (GEE) is used as a workspace in a whole series of computing activities.

Figure 4. Schematic diagram of bathymetry extraction based on Li *et al.* (2021) method in Anakan Bay – Pacitan and Kemujan Island – Karimunjawa Archipelago



PlanetScope Satellite are fully processed using GEE. The image chosen is the image with the clear visibility without cloud or water sediment content. The method developed by Li *et al.* (2021) for extracting water depth uses a chlorophyll value approach that remains constant over time. (Chl-a = 0.29 mg/m^3) as input to calculate the values of m_0 and m_1. Land and water are separated using the NDWI transformation scheme. The depth predictions obtained were then tested for accuracy to determine SDB capabilities using the method developed by Li *et al.* (2021) around the waters of Anakan Bay - Pacitan, and Kemujan Island - Kep. Karimunjawa. The accuracy test was carried out using R^2 and RMSE value calculations.

5. Accuracy Assessment

Accuracy assesment were carried out to determine the capabilities of the method developed by Li *et al.* (2021) using the R2 and RMSE approaches. The sample points used to carry out accuracy tests are on Kemujan Island.

$$R^2 = 1 - \sum_1 \left(h_i - h'_i\right)^2 / \sum_i \left(h_i - h''_i\right)^2$$

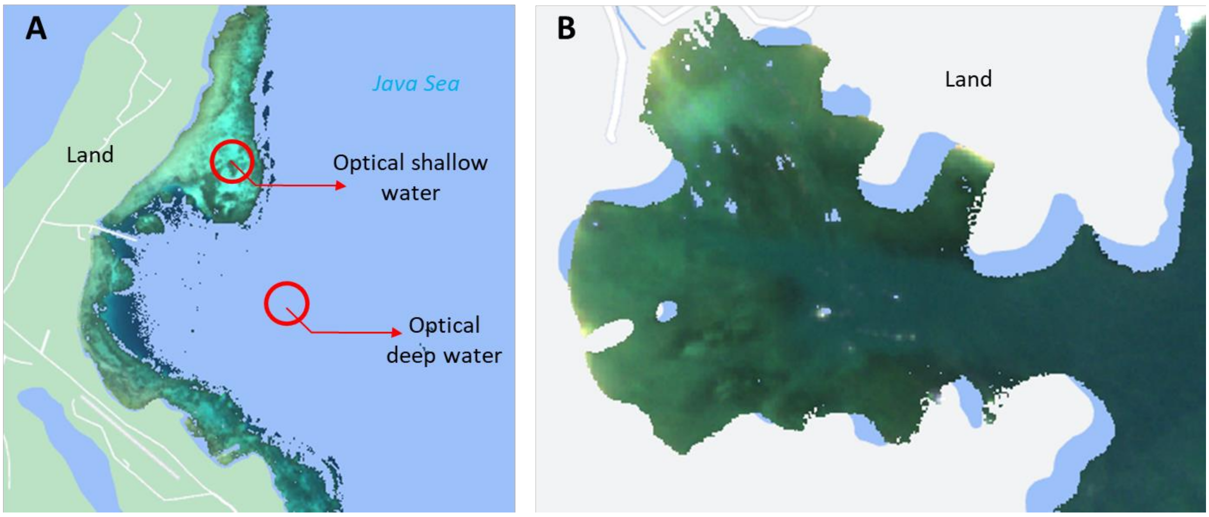
$$RMSE = \left(\sum_{i=1}^{n} \left(h_i - h'_i\right)^2 / n\right)^{0.5}$$

6. Research Result and Discussions

6.1 Clean Water Extraction of Shallow Water

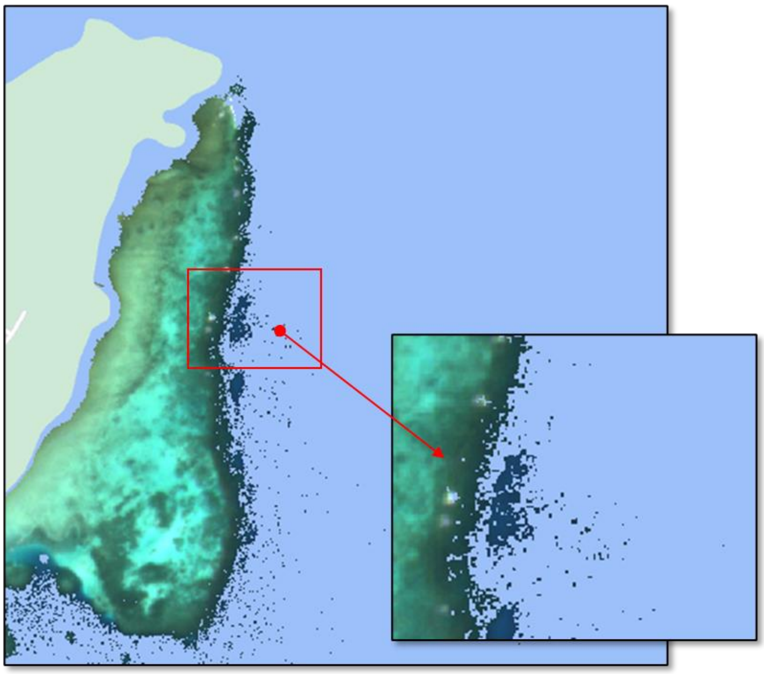
The clean water mosaic was selected based on the best image by manually selected with the minimum cloud content, and the absence of breaking waves and sunglints, during eastern season (june to august 2023), which is the season closest to when this paper was written. Image acquisition with a mosaic of clean water at both locations is shown in Figure 5. In both images, it appears that the shallow waters are free from various kinds of disturbances (*i.e.* clouds, waves and sunglints). From figure 5 it can be seen that the entire land has been systematically separated from the water area.

Figure 5. Results of separating land and water using NDWI transformation



In contrast to the clean water mosaic developed by Li *et al.* (2021) which still maintains the optical deep sea, in this study the optical deep water is completely removed using NDWI transformation. Through optically shallow waters, Wicaksono, (2015) stated that the spectral reflectance value can reduce bathymetric information based on passive system remote sensing images. NDWI computation via GEE will produce negative values for land and positive values for waters. However, specifically, shallow water in the NDWI results is limited by a pixel value of 0.27, so pixel values above this value are considered shallow water, while values below 0.27 are automatically considered deep sea and are removed in the calculation. The imagery then cropped using NDWI with a pixel value of > 0.27 for Kemujan Island and > 0.2 for Anakan Bay. The value are produce from manually trial and error. Unlike cutting using polygon geometry, NDWI-based deep water filtering produces residues in deep water that are not completely cut (see figure 6). In this research, the residue was retained and no further filtering was carried out, and produced a mosaic of clean water for the waters on Kemujan Island and Anakan Bay in Pacitan.

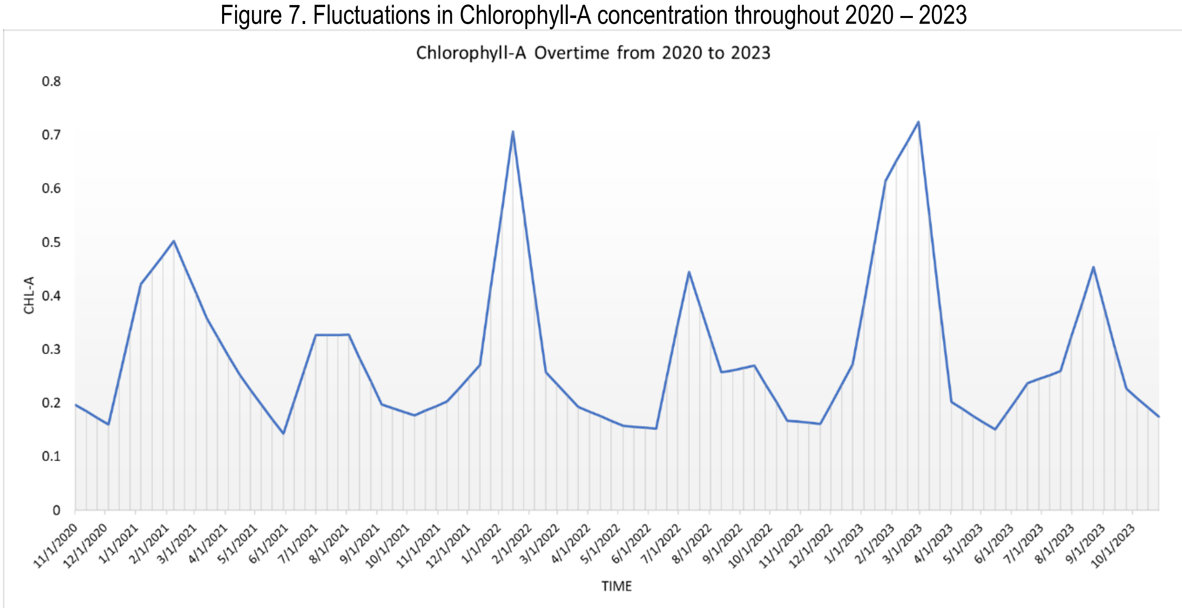
Figure 6. The residue produced by filtering between deep sea and shallow sea optically uses NDWI



6.2 Bathymetry Extraction Result Analysis

The shallow water bathymetric extraction developed by Li *et al.* (2021) uses Chlorophyll-A as input to calculate the parameters m_0 and m_1. Chlorophyll-A around the study area, especially in the Kemujan Islands region throughout 2020 - 2023 has an average of 0.29 mg/m³ with the following fluctuations:

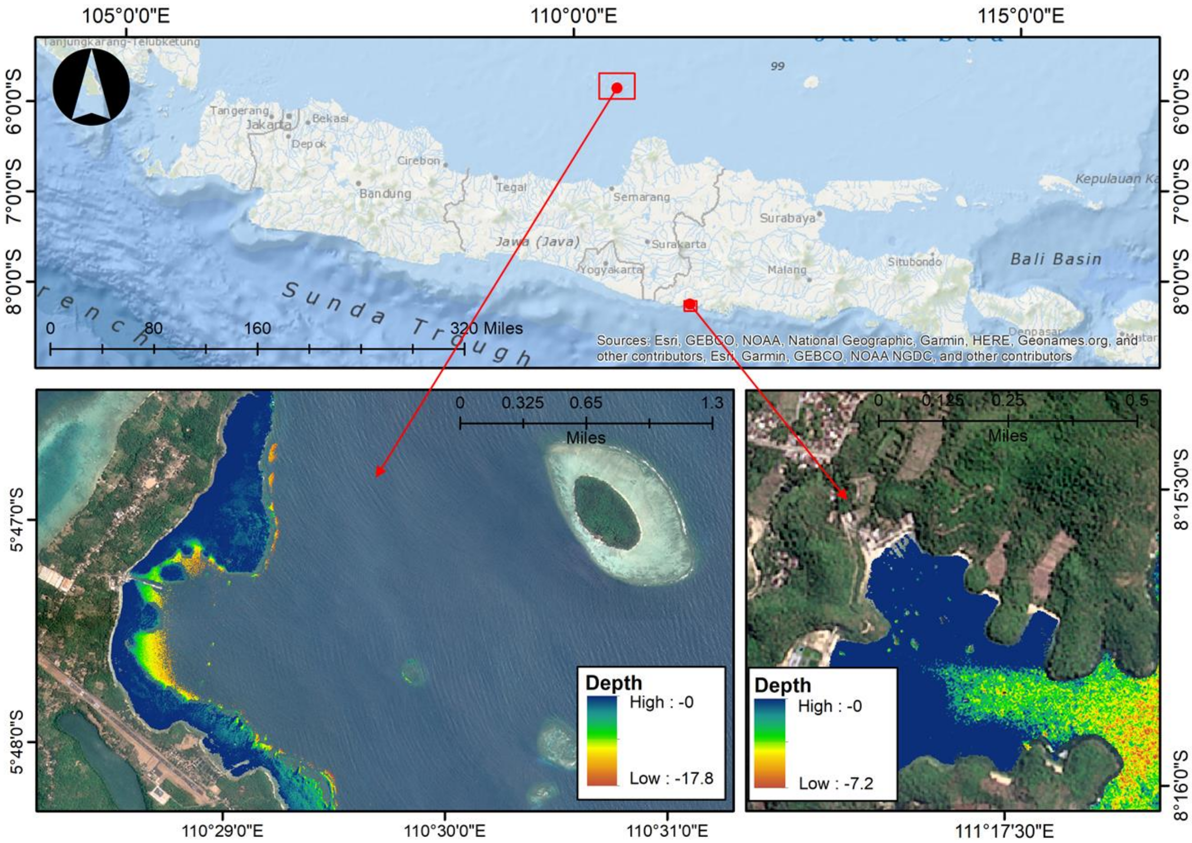
Figure 7. Fluctuations in Chlorophyll-A concentration throughout 2020 – 2023



Source: Processed from https://data.marine.copernicus.eu/

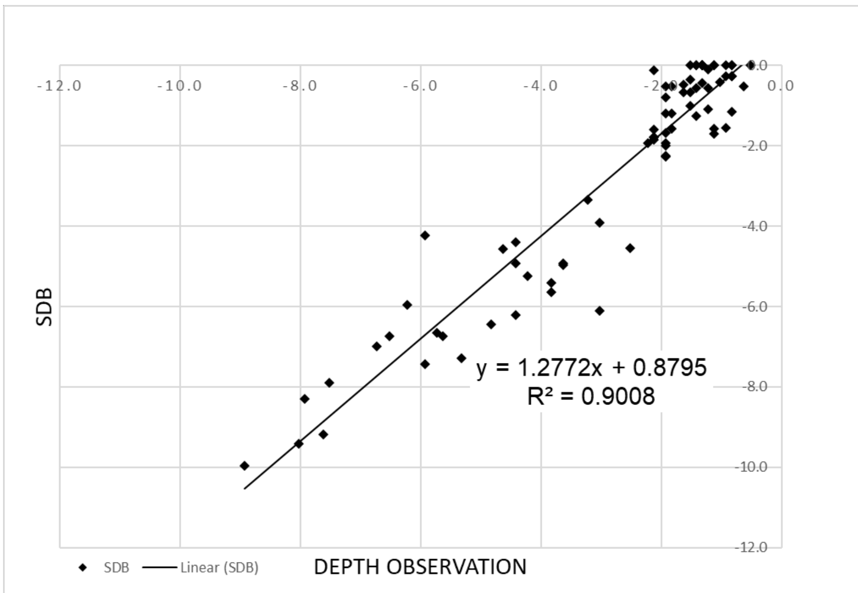
The graph shows fluctuations in the concentration of Chlorophyll-A over time, it can be seen that at some moments the concentration of Chlorophyll-A is much higher than in other months, so the average value is a reasonable consensus that can be used. By using a cloud-based computing platform - Google Earth Engine (GEE), computing processing time can be reduced more efficiently to less than one minute (depending on the network used). The depth value produced through SDB processing in the waters of Kemujan Island ranges from 0 to -17.8 meters, while in the waters around Anakan Bay - Pacitan the depth that can be obtained is in the range 0 to -7.2 meters (see Figure 8).

Figure 8. Shallow water bathymetry on Kemujan Island (left), and Anakan Bay in Pacitan (right).



Based on the validation points in Figure 2, we carry out accuracy tests using the R^2 and RMSE formulations. Calculation of the R^2 value shows that the value obtained is 0.9 (see Figure 9). This value shows that the model was built using an algorithm Li *et al.* (2021) could represent depth variation around 90%. Furthermore, based on RMSE calculations, the accuracy obtained reached 1.1 meters. Through the R^2 and RMSE results, it can be seen that the accuracy is still adequate. Even though that the SDB results in the waters of the study area cannot yet be fully used for maritime applications that require precise accuracy. In general, the SDB results can be used as academic study material and regional overviews, because until now the only bathymetry data that is freely available is the National Bathymetry (BATNAS) from the Geospatial Information Agency (BIG) and global bathymetry data from GEBCO.

Figure 9. Validation of the bathymetry model with depth measurements in the field



These two independent bathymetry sources are still unable to describe shallow waters optimally because they have 6-arcsecond and 15 arcsecond resolutions, so the method developed by Li *et al.* (2021) can be a solution to fill the gaps in shallow water bathymetry data in the study area. The advantage of this method is that it does not require a depth sample as is often used by other methods as an input predictor for making shallow water bathymetry models.

Conclusions and Further Research

The shallow water bathymetry mapping method with the algorithm developed by Li *et al.* (2021) is able to extract shallow water bathymetry without using depth samples as is done by other empirical methods. Our research provides the computational framework in a cloud platform using the Li *et al.* (2021) SDB algorithm and produce adequate accuracy with an SDB result of 90% that can represent the optical shallow water in the area, and the RMSE result is 1.1 meters.

Acknowledgments

The author thanks Universitas Gadjah Mada, where this research was funded by Gadjah Mada University through the Universitas Gadjah Mada Final Project Recognition Grant scheme Number 5075/UN1.P.II/Dit-Lit/PT.01.01/2023 or Universitas Gadjah Mada RTA Program with the Grant Number 5075/UN1.P.II/Dit-Lit/PT.01.01/2023, and PlanetScope to provide the imagery data.

Credit Authorship Contribution Statement:

Nurul Khakhim: Conceptualization, Investigation, Methodology, Formal analysis, Writing – original draft, Supervision, Data curation, Validation, Visualization, Funding acquisition

Agung Kurniawan: Methodology, Project administration, Software, Writing – original draft, Data curation, Validation, Writing – review and editing, Visualization.

Pramaditya Wicaksono: Methodology, Software, Formal analysis, Writing – original draft, Supervision, Data curation, Validation, Writing – review and editing, Visualization.

Ahmad Hasrul: Project administration, Software, Data curation, Validation, Visualization, Funding acquisition.

Declaration of Competing Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Journal DOI: https://doi.org/10.14505/jemt
Journal's Issue DOI: https://doi.org/10.14505/jemt.v15.1(73).00